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Impacts of multiple stressors on mountain communities: Insights from an agent-based model of a Nepalese village

Nicholas Roxburgh [a], Lindsay C. Stringer [b,*], Andrew Evans [c], Raj K. GC [d], Nick Malleson [c], Alison J. Heppenstall [c]

[a] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[b] Department of Environment and Geography, University of York, York, YO10 5NG, UK
[c] School of Geography, University of Leeds, Leeds LS2 9JT, UK
[d] School of Public and International Affairs, Virgina Tech, Blacksburg, VA 24060, USA

A R T I C L E I N F O

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A B S T R A C T

Mountain communities in developing and transitioning countries are experiencing a period of rapid social, economic, and environmental change. While change has long been a feature of mountain life, the rate, magnitude, nature, and number of the transformations now taking place is unprecedented, with profound implications for the sustainability and welfare of mountain communities in the coming years. It is therefore vital that their potential impacts be understood. Considering stressors in isolation can give a false picture as each stressor alters the context within which the other stressors are operating. Holistic approaches are needed. In this paper, a variety of stressors are concurrently simulated within an empirically informed agent-based model of a rural Nepalese mountain community so that their combined impact can be studied. The potential effect of changing fertility rates, increasing crop yield variability, and earthquakes on household finances is considered for the period 2015–2030. Results show that higher fertility rates, increased crop yield variability, and earthquakes all have negative long-term effects on household finances, and that each of these stressors compounds the effect of the other stressors in an additive fashion. Results further highlight heterogeneity in the capacity of households to cope with stressors and demonstrate the important role that happenstance can play in exacerbating the effect of stressors. Our findings suggest that development practitioners should explicitly take multiple stressors into account when considering interventions. They should also contemplate improved microtargeting of households to increase aid effectiveness over the longer term, while recognising that household vulnerability is often dynamic.

1. Introduction

Recent estimates suggest that thirteen percent of the world's population reside in mountainous areas (FAO, 2015); the vast majority in rural communities in developing or transitioning countries. While change has long been part of mountain life, the current rate, magnitude, nature, and number of transformations is unprecedented (Wang et al., 2019). Many areas have seen dramatic population growth, increased pressure on land and resources, climate changes, large scale youth emigration, increased inflow of remittances, improved connectivity and service provision, and a growing penetration of capitalism with a consequent reorientation of agricultural economies (Körner et al., 2005; Parish, 2002). Alongside these trends, communities must continue to deal with age-old challenges like pests, diseases, and natural hazards. Together, these factors have profound implications for the future sustainability and welfare of mountain communities, yet present understanding of what these implications may be is limited.

The multifarious and concurrent nature of the processes – or stressors – poses a particular challenge. Studying stressors in isolation, as is typical, can give a false picture. Each stressor alters the context in which the other stressors are operating, with stressors potentially interacting in nonlinear ways, possibly changing their nature in fundamental ways compared to their lone operation (Crain et al., 2008; O'Brien et al., 2009; O'Brien and Leichenko, 2000; Olsson et al., 2014). For policy formulation, development planning, and local decision making, this has important implications. If stressors are considered independently, erroneous conclusions may be drawn, potentially leading to sub-optimal, redundant, or even conflicting responses and a lack of policy

* Corresponding authors.
E-mail address: lindsay.stringer@york.ac.uk (L.C. Stringer).

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coherence (Schipper and Pelling, 2006). Consequently, there is a clear need for a holistic approach to the study of multiple stressor contexts.

Literature is slowly emerging, largely from the climate change, development, vulnerability, and resilience research fields, that explicitly considers the impact of multiple stressors on socio-ecological systems (Antwi-Agyei et al., 2017; Casale et al., 2010; Eakin et al., 2014; Eakin and Wehbe, 2009; Eriksen and Silva, 2009; Martin et al., 2016; O'Brien and Leichenko, 2000; Olsson et al., 2014; Reid and Vogel, 2006; Schipper and Pelling, 2006; Tschakert, 2007). This work has produced several valuable insights but has tended to focus on past and present stressor contexts. In contrast, this paper focuses on how multiple stressors could affect mountain communities in the longer-term – in the period up to 2030. Having a clear sense of potential challenges and opportunities ahead is important because it enables more effective planning for the future and could help to avoid maladaptation. Focus on the period to 2030 is roughly in line with stakeholder planning horizons.

Considering future stressors requires an approach that can explore the effects of a range of hypothetical stressor scenarios. Agent-based modelling (ABM) is ideally suited to this as it can be used to simulate the interaction and co-evolution of multiple components and processes, capturing the complex dynamics at play in stressor afflicted rural mountain communities. ABMs can also be used as *in silico* labs for controlled, repeatable experiments. This is rarely available to social scientists who rely on real-world data or theory (Oreskes et al., 1994; van der Leeuw, 2004). Furthermore, they allow for sophisticated modelling of individual human cognition and behaviour (Miller and Page, 2009; Moss and Edmonds, 2005; Schlüter et al., 2017). In the context of stressor research, this is important because it allows the potential for ongoing human learning and adaptive behaviours to be considered (Filatova et al., 2016; Porter et al., 2014). ABMs also enable the effect of stressors to be analysed at both village and household scales. Multi-scale approaches are relatively novel within the multiple stressors literature, yet important because experience of stressors is mediated across scales. Averaging outcomes at one scale can mask disparities in experience at smaller scales.

This paper uses an ABM to examine the potential impact of multiple stressors on a mountain village in Nepal over the period 2015–2030. The model incorporates all the main social and ecological systems at the field site the model is based on, and is populated with artificially intelligent agents designed to behave in ways that attempt to match how real villagers behave – interacting with their environment and one another, making decisions based on their beliefs and needs, and learning from experience. Within this model we simulate the effect of increasing crop variability, declining fertility rates, and earthquake events on village demographics and household finances. These stressors were chosen because they were all particularly pertinent at the project field site and exemplify the types of challenges currently experienced in mountain systems around the world (Wang et al., 2019). By considering them together, we are able to explore the combinatory effect of both gradual- and rapid-onset processes and events - something that few studies have previous attempted (Olsson et al., 2014). We ask:

a. How do the stressor scenarios affect the demographic and financial trajectory of the study village and its households?
b. How do the stressors interact with one another and to what extent does their impact depend on the context in which they occur?
c. How do household attributes mediate experiences of stressors?

2. Research design and methodology

A case-study based modelling approach was chosen whereby an in-depth ethnographic study of a single village informed the design of an ABM. Case-study approaches are advantageous in that they allow complex phenomena to be explored within their context, (Ford et al., 2010; Yin, 2008) and facilitate acquisition of deep, rich understanding of the systems in question which can usefully support model design and parameterisation (Yin, 2008). Grounding the model in a real world field site offers a clear baseline for validation and can help keep models naturalistic (Janssen and Ostrom, 2006). Careful field site selection ensured the chosen location was reasonably illustrative of other mountain communities. A sensitivity analysis was also performed to provide an indication of how robust findings are likely to be to different contexts.

Nepal's hills and mountains offer an example *par excellence* of an area experiencing multiple stressors and undergoing rapid change (Gerlitz et al., 2014). To identify a field site that was reasonably representative of a mountain community experiencing multiple stressors, a two-part purposive selection approach was used. First, we shortlisted villages that met a preliminary set of criteria, primarily related to geographic location, known regional exposure to stressors, accessibility, and population size (*SI Appendix 1*), based on data from an International Non-Governmental Organisation gathered in the year prior to the fieldwork. Second, we visited the three shortlisted sites and assessed them against criteria including their representativeness, stressor experience, and willingness to participate in the study (*SI Appendix 2*).

The chosen site lies several hours north-east of Kathmandu in the mountain district of Dolakha. It is referred to in this paper by the pseudonym Namsa, in line with ethical approvals given for the work. Livelihoods in Namsa are primarily agro-pastoral, with each of the 14 households owning its own smallholding and producing output for both home consumption and sale. Recent decades have seen population growth, construction of a nearby road, improved access to schools and medical services, and progressive incorporation into Nepal's monetary economy. The latter is manifest in an increase in the amount of off-farm paid labouring undertaken and a steady shift towards growing cash, rather than subsistence, crops. More recently, there has been an intensification in cash crop cultivation, and increasing numbers of young adults – particularly men – who have sought work elsewhere in Nepal or in the Middle East, where huge numbers of Nepalese are now employed (Pattisson, 2013). There has also been a substantial reduction in the fertility rate with many people now desiring small families in the hope it will help them maximise their children's life chances - a trend that is occurring nationally (MHP, 2012). Though not yet strongly pronounced, there has additionally been a notable change in local climate, with snow and frosts increasingly infrequent during winter despite the village lying at 2,000 m above sea level, and unseasonal weather events increasing in frequency (DHM, 2015).

On 25 April 2015, while we were concluding the initial data collection, Namsa experienced the 7.8Mw earthquake that struck a large swathe of the country, and over the subsequent days and weeks felt the effects of numerous aftershocks (NCEI, 2017; Roxburgh et al., 2000) . Tremors caused severe damage to dwellings, razing several of them. While the earthquake could not have been predicted at the outset of the study, it provided a valuable opportunity to gather data on how such shocks can affect mountain communities alongside slower moving stressors.

2.1. Data collection and analysis

The majority of the fieldwork was conducted between February and April 2015, with a week-long follow-up visit in March 2017. The first phase gathered data necessary to design and parameterise the ABM in a thorough and systematic way and included information on almost every aspect of village life. Trajectories of change and possible future pathways the change could take were also explored. Emphasis was placed on documenting processes and decision making, in order to support their recreation in virtual form. The follow up visit gauged the impact of the April and May 2015 earthquakes on Namsa and provided feedback on tentative ABM designs as part of the model validation process.

A variety of data collection techniques were employed during the first phase, including village walks and mapping, process tracing, household surveys, focus groups, and development of a village wiki. Village walks and mapping helped us familiarise ourselves with the setting and to re-introduce ourselves to the villagers. With the process tracing (Bennett and Checkell, 2015), four community members were shadowed for a day to establish individual daily schedules and time budgets. Asking participants to describe their actions in real time, along with the reasoning behind them, offered insights into their life worlds and decision-making. As villager experiences differ, we recruited individuals from across the age spectrum and from both genders. Household surveys, meanwhile, provided data on household composition, assets, finances, livelihoods, farm characteristics, food security, and preferred coping mechanisms alongside age, gender, educational attainment, occupation information, and household duties of individual household members. This data was particularly valuable for parameterising the ABM. Seven focus groups explored people's perceptions, opinions, and experiences across a range of topics, allowing five to twelve people per group to describe and explain the complexities of their lives (Valentine, 1997; see SI *Appendix 3* for details). The interactive nature of focus groups aided recall of historical events and factual information as participants questioned and prompted one another, facilitating exploration of pooled memory and experience. Finally, the wiki created a comprehensive summary about the village and its surrounding area. One male and one female villager (both aged 26) provided details on a wide range of topics. Responses were typed up as mini articles by the research assistant. The hierarchical, interconnected, almost algorithmic logic of wikis closely fits the logic of ABM design – reducing complex systems to neat, digestible elements without divorcing these elements from context.

Secondary sources supplemented the field data (SI *Appendix 4*). Data gathered using the various methods was subsequently incorporated into the wiki, contents of which then guided the model design process.

2.2. The model

A full description of the model is provided in Roxburgh et al. (submitted for publication), structured in accordance with the ODD protocol (Grimm et al., 2010, 2006) (a standardised protocol for describing ABMs). A summarised version is provided below. The model includes all the main processes identified during fieldwork that influence village economics and demographics and that interact in a substantive way with our three focal stressors. While several factors are at play, individual processes are depicted in a relatively parsimonious fashion. We sought to capture important system characteristics and behaviours while avoiding creating something of Daedalian complexity. The parameters were primarily informed by the fieldwork, although other sources were occasionally drawn upon and certain parameters were calibrated (Roxburgh, 2019).

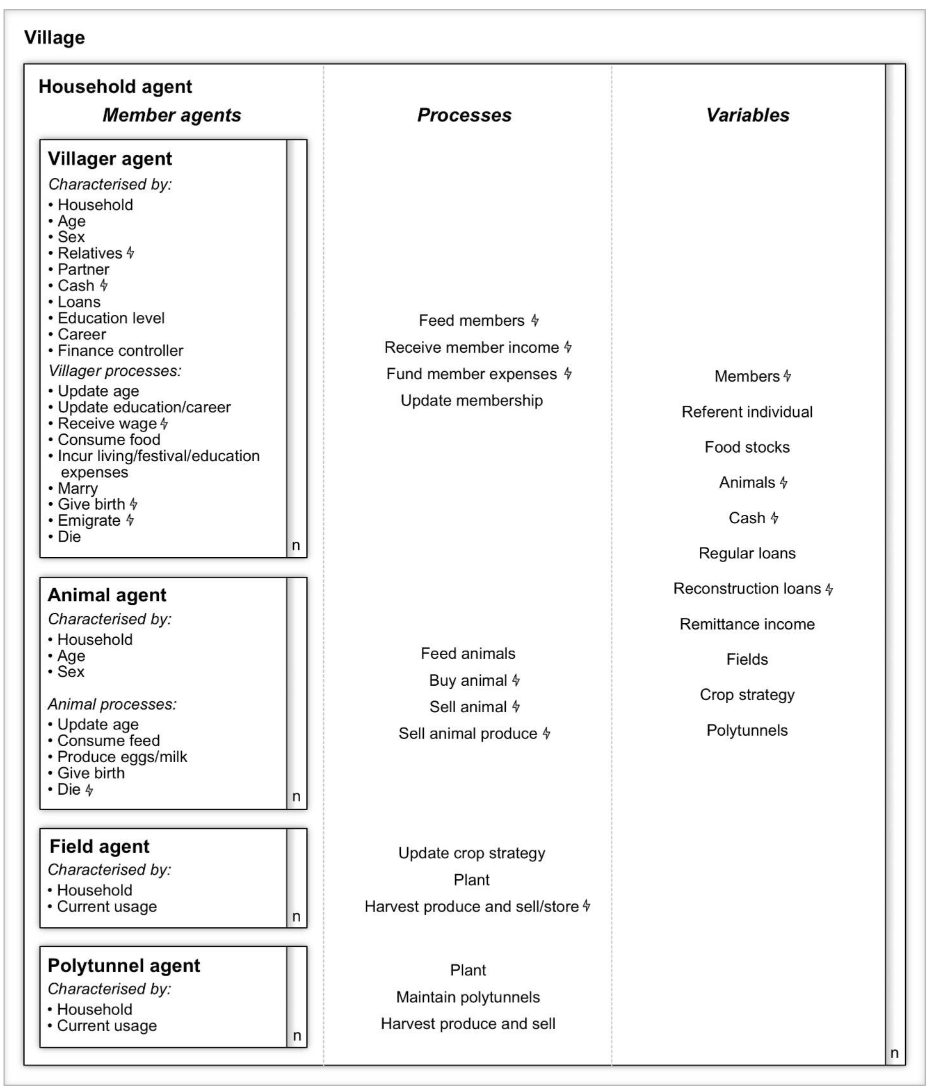

Fig. 1. A conceptual diagram showing a simplified representation of agent variables, processes, and interactions. The lightning bolts show the variables and processes that are directly affected by the stressor scenarios.

2.2.1. Entities, state variables, and scales

The model consists of eight entities: villagers, households, chickens, goats, cattle, buffalo, fields, and polytunnels. Villagers are primarily characterised by their gender, age, household, education, and career, with variables stating the timing of their marriage and their death which are either determined at model initialisation or at birth. Married women have additional variables stating their desired number of children and the timing of their next child's birth. Households are primarily characterised by their members, fields, polytunnels, livestock, and finances. Animals are characterised by the household they belong to, their age, and gender. Fields and polytunnels are characterised by the household they belong to and their current usage. Fields can be planted with maize, millet, wheat, rice, potato, cabbage, or cauliflower, while polytunnels are used for growing tomatoes. Each field equates to half a ropani of land (254.35 m^2), each polytunnel to 68.34 m^2, and one time-step corresponds to one day. Simulations run for fifteen years, beginning 1 January 2015. A conceptual diagram showing the relationship between the entities, as well as their associated variables, is provided in Fig. 1.

2.2.2. Process overview and scheduling

On each time-step, the simulation advances by one day, and villagers' ages update. They then determine whether their education status or career should be updated and whether they are due to receive a salary, wage, or pension. The former depends whether they have reached an education or career juncture, while the latter depends on their current career status and the day of the month. Next, the personal expenditure of each villager is determined. Villagers not working abroad will incur food expenses, plus non-specific other living expenses. Those attending school or college may also incur education expenses. If the current day is one of the 23 annual festival days, villagers additionally incur festival expenses. Following this, checks are performed on each villager to see whether they are due to die, marry, or give birth on the current time-step. These events are actioned as needed.

Animal agents also update their age on each time-step, and consume set quantities of feed, with costs borne by their household. At set ages, female animals give birth or, in the case of hens, lay eggs. In the model, all eggs, kids, and calves are sold immediately. For a period post-birth, cow and buffalo agents yield milk. It is assumed that households sell any surplus milk, with the amount depending on the number of household members. At set ages, the chickens, goats, and buffalo are sold for slaughter. Cattle simply die – law prohibits their slaughter. When animals that reach their maximum age, are sold or die, they are immediately replaced with a younger animal of the same species.

Households begin each time-step by checking whether the current day is a crop planting or harvesting day. If the former, households reevaluate their existing crop strategy to determine how many fields, if any, they wish to allocate to the relevant crop. Their assessment considers their land holdings, the expected yield and sale price of the crops, the need to generate fodder for animals, and other land allocation conventions. Planting then takes place – which has costs associated with it. If the day is a harvesting day, fields are harvested, and crops sold. The money received depends on the market price of the produce and the yield – the latter determined by a quasi-stochastic process. Newly harvested fields then become available for planting again. As with planting, harvesting has certain costs.

If households own polytunnels, on set days they receive income from tomato harvests and incur cultivation expenses. Should the time-step correspond to the first day of a month, any households designated as in receipt of a remittance will receive it. A check is performed to determine whether household fission should occur. This typically happens when a married adult male who is still living with siblings accumulates sufficient funds to construct his own house. The individual will be gifted a portion of his parent household's land to start his own farm which he will move to with his wife and any children they have. After assessing whether fission should occur, households consider whether their circumstances have changed such that they need to buy or sell livestock and/or poultry – the number they own is deterministically linked to the number of adult members and the size of their land holdings. Finally, households assess their financial state, taking into account their latest income and expenditure. Within this process, they consider how many portions of meat they can afford each week without compromising their future financial security. Meat consumption is modelled as it represents the main luxury expenditure outside of festival times. Those households with negative net finances cannot afford meat and pay interest on their debts.

Households typically receive member income and cover member expenditure. However, there is an important exception. Married adult men who still live with younger male siblings manage their own finances, along with the finances of their wife and any children they may have. This financial independence allows them to accumulate funds to set up their own household at a later date. As the youngest male sibling typically inherits the parents' household farm once his brothers have departed, this financial independence will not apply to him. One caveat is that financially independent individuals provide financial support to their parent household should the household otherwise be destined to enter into debt.

2.2.3. Initialisation

For the model to provide useful insights into the future evolution of villages like Namsa, the initial model conditions need to be realistic, yet, it would be inappropriate to simulate the fate of actual people and households. Consequently, a bespoke population synthesis method was used to generate households, villagers, and assets that do not directly mimic what was observed at the fieldsite, but which are statistically, structurally, and qualitatively similar to it. The approach ensures the initial simulation conditions approximate the mix of household types at the fieldsite, and that individual household and villager attributes and associations are reasonable. Initial conditions vary slightly between each simulation due to stochastic elements in the synthesis process. However, the initial number of households generated is always 14 (the number of households present when data was collected). Further details of the initialisation process, including a thorough explanation of the population synthesis process, are provided in Roxburgh et al. (submitted for publication).

2.2.4. Simulation experiments

Three main stressor types were considered - earthquakes, changing fertility rates, and increasing crop yield variability - because they are representative of contemporary challenges faced by many mountain communities (Mainali and Pricope, 2017; Nibanupudi and Shaw, 2015; Shakya and Gubhaju, 2016) and were particularly pertinent to the villagers in Namsa, as became apparent during data collection. For each stressor, two scenario pathways were crafted, informed by experiences and expectations of the villagers, as well as national trends.

Each model run simulates one of the earthquake pathways, one of the fertility pathways, and one of the crop variability pathways. This means that there are eight potential pathway combinations. For each pathway combination, two-hundred simulations were run. Detailed explanation justifying this number of runs is in Roxburgh et al. (submitted for publication), along with discussion of the model validation process, and the results of a sensitivity analysis.

Stressor scenarios

***Earthquake pathways*:** The first earthquake pathway attempts to mimic the social and economic impact of the 2015 earthquakes. Impacts include loss of livestock, decreased yields, emigration of households, changes in labour market opportunities, and reconstruction costs. The second earthquake pathway is a counterfactual: the earthquakes do not happen and the impacts are not realised.

***Fertility pathways*:** The first fertility scenario assumes an average fertility rate of 1.6 children per woman; the second assumes 2.1 children per woman. Both rates are equally plausible for Namsa over the short- to medium-term based on village

(*continued on next page*)

(*continued*)

discussions and recent demographic reporting for Nepal (MHP, 2012). The lower rate tallies with the current urban fertility rate, while the higher rate is the Nepalese government's long-term national target (KC et al., 2016).

***Crop variability pathways*:** The first crop variability scenario assumes continuation of the status quo in terms of inter-annual yield variability, while the second scenario assumes a higher degree of inter-annual yield variability than is currently reported. This latter is intended to represent potential consequences of climate change and the increasing threat of agricultural pests and diseases. Here, variability is defined by the half-yield recurrence interval. For subsistence crops, the status quo half-yield recurrence interval is 12-years, dropping to 9-years for the alternative scenario. For cash crops, the status quo half-yield recurrence interval is 10-years, dropping to 7-years for the alternative scenario.

3. Results

3.1. *Demographic impact of scenarios on the village*

A reduction in the average number of households and villagers by 2030 was seen under all pathway combinations (Fig. 2). The earthquake-affected simulations were associated with an average fall in the household count of 11.57% and an average fall in the villager count of 7.87%, slightly greater than the respective 8.79% and 6.86% falls seen when the earthquakes did not occur. The fertility rate scenario, meanwhile, appears to have had no substantive impact on the household count, but it did have a considerable effect on the 2030 villager count. Under the higher fertility rate scenario, the number of villagers declined by an average of 4.33%, while under the lower fertility rate scenario the decline was 10.40%. In regards average household size, the fertility rate scenario again had the greatest impact, with the higher fertility rate leading to a notable increase in average household size of 7.28% while the lower rate leads to a nominal fall of 0.27%. The earthquakes, meanwhile, result in a slightly larger rise in average household size (4.31%) than the rise that occurs in their absence (2.43%). The crop variability rate had no substantive effect on any of the demographic outcomes.

Regarding age structure, the 15.64% fall by 2030 in the average number of 18–60s and the 26.41% rise in the average number of over-60s are notable. While the earthquake has a slight depressive effect in each case, influence of the fertility and crop variability rates was minimal. The impact of the scenarios – or more specifically, the fertility rate – was much more pronounced in the case of the under-18 count. The higher fertility rate scenario results in a slight rise of 2.38% in the number of under-18s relative to the 2015 average, while the lower rate results in a substantial fall of 21.65%.

The third column of Fig. 2 shows the effect on the response variables of different pairs of stressor levels. Interaction effects would be signalled

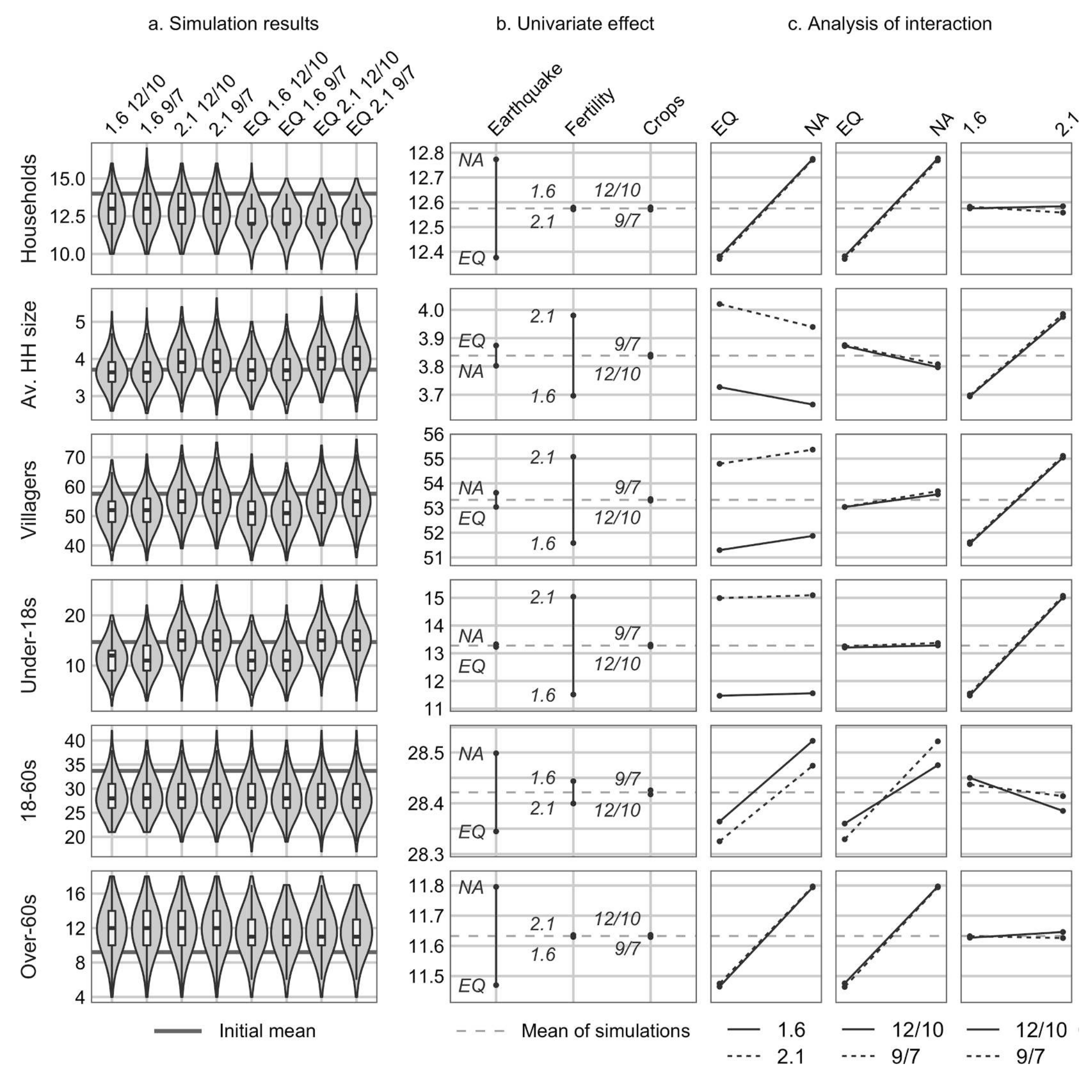

Fig. 2. Demographic outcomes of the simulations. EQ and NA indicate whether earthquakes are simulated or not; 1.6 and 2.1 indicate the average fertility rate; 12/10 and 9/7 indicate the half yield crop variability rate with the first number representing the rate for subsistence crops and the latter the rate for cash crops.

by differences in slope. However, no qualitatively meaningful differences are observed.

3.2. Economic impact of scenarios on the village

The financial outcomes of the simulations are shown in Fig. 3. Whether the earthquake occurs or not is the main factor differentiating the scenario combinations in terms of both village income and village expenditure. On average, total village income is 5.01% greater in simulations in which earthquakes did not occur, while village expenditure is 6.15% lower. The crop variability scenario also has a tangible effect on village income, but not on village expenditure – village income under the higher crop variability scenario is 1.10% less on average than under the baseline crop variability scenario. Conversely, the fertility rate has a tangible effect on village expenditure, but not on village income – village expenditure is 2.65% lower under the 1.6 scenario than it is under the 2.1 scenario.

Household cash and debt results share similarities with village income and expenditure results. Total household cash in 2030 is, on average, 27.82% lower in earthquake affected simulations than under the counterfactual scenario, while total household debt[1] is 34.52% higher. Although the magnitude is less, the higher fertility and crop variability scenarios also negatively affect total household cash, while increasing total household debt. Notably, the magnitude of the earthquakes' and the fertility rate's impact on household cash is substantially more than it is on household debt, with the reverse in the case of crop variability.

The earthquake scenario, once again, has the greatest impact when it comes to the total household debt days experienced, with fertility and crop variability scenarios trailing some way back but still having a meaningful effect. Interestingly, however, the impact of the crop variability scenario is qualitatively negligible when it comes to the number of households ever experiencing debt. Only the earthquake ($\Delta = 1.04$) and fertility rate ($\Delta = 0.25$) had a substantive impact. As with the demographic response variables, no qualitatively meaningful interaction effects between stressors are observed in respect to any of the response variables (see Fig. 3 column *c*).

Household net finance values for 2030 are disaggregated by quartile in Fig. 4, revealing important intra-village disparities in household financial performance, and demonstrating the value of taking a multi-scale approach. The minimum net finance figures tend to represent households caught in debt spirals wherein they are unable to pay-down their debts and are pulled ever further into the red by interest charges. In most cases, these households are characterised by lack off-farm income sources, though there are exceptions. The maximum figures also exhibit a certain run-away characteristic as they tend to represent households whose annual income consistently exceeds expenditure thanks to salaried employment. The lower quartile figures, meanwhile, hover around zero, with the median typically just above it for simulations in which earthquakes did not occur, and just below it when earthquakes did occur. Notably, the lower quartile value range is unusual in its degree of constraint. As households within this finance bracket are typically either at risk of, or already in, debt, they will often be pursuing coping strategies to keep themselves in, or return themselves to, the positive side of the zero line. Essentially, positive household finances become sticky-down as they approach this line, while negative household finances experience a degree of upward pull towards it. The sticky-down phenomenon is also evident, to a lesser degree, in the median and upper quartile finance brackets.

3.3. Impact of other shocks and stressors

Alongside the main earthquake, fertility rate, and crop variability scenarios, a number of additional shocks and stressors can occur during the simulations. Fig. 5 gives an indication of their potency in precipitating entry into debt, showing the percentage of households with positive net finances for at least twelve months prior to a shock or stressor that go on to experience debt during the twelve months following an event. Deaths appear most closely associated with households getting into financial difficulty – 38.22% of households dip into the red within a year of experiencing one. Next come weddings at 10.28%, followed by subpar potato, cabbage, and millet harvests at between 4.56% and 5.68%. Replacement of an ox or cow is associated with a debt entry rate of 4.44%, while the degree to which wheat, cauliflower, and maize harvests are subpar makes no substantive difference to the number of households subsequently entering into debt. This suggests that these particular events are not important debt triggers and that debt entrances in these cases are largely coincidental. Indeed, a certain baseline likelihood of households experiencing debt can be expected, regardless of whether a particular event occurs or not. Complicating matters, this baseline differs between shock and stressor types due to the differential exposure of households and the financial security of these household groups. Thus, the figures should not be viewed as an unmediated indicator of event potency.

3.4. Role of household attributes in determining vulnerability to stressors

Here, we look at the association between various household attributes and household financial performance. Recognising that the role of attributes may change over time, the analysis considers three distinct time periods: 2015–2019, 2020–2024, and 2025–2029. For each period, Kendall's tau-b correlation assessed the strength and direction of the relationship between changes in household net finances over the time period and nine household attributes. The attributes were chosen because they constitute the main determinants of household income and expenditure in the model. Results are presented in Table 1.

Polytunnels ($\tau b \geq 0.307$ and ≤ 0.313) and salaried members ($\tau b \geq 0.269$ and ≤ 0.392) have the strongest positive concordance with changes in household finances, although these correlations can only be considered moderate. The polytunnels correlation coefficient is relatively stable across time periods, but the salaried members coefficient grows in strength, likely because of salaried individuals receiving promotions. Waged members ($\tau b \geq 0.113$ and ≤ 0.238), pensioned members ($\tau b \geq 0.188$ and ≤ 0.249), and members abroad ($\tau b \geq 0.113$ and ≤ 0.238) are also associated with positive changes in household finances, but the strength of the relationship is not quite as strong in the case of polytunnels and salaried members, especially in the latter time periods. In contrast to the attributes thus far, non-earning adults ($\tau b \leq -0.192$ and ≥ -0.289) have a negative concordance with changes in household finances across all of the time periods. This is also true for youth dependents, although the correlation is only statistically significant for the latter two time periods and is notably small ($\tau b \geq -0.149$ and ≤ -0.054). Land holdings have very little effect on the financial performance of households when viewed from a village scale perspective ($\tau b \geq -0.081$ and ≤ 0.022).

To assess whether the correlations are affected by the scenarios, Kendall's tau-b correlation was run again for each attribute-finance combination but with the data disaggregated by scenario. Results show no major differences in correlations between the scenarios (see *SI Appendix 5*).

4. Discussion

4.1. Impact of stressors on financial and demographic trajectories

4.1.1. Earthquakes

In scenarios in which the earthquakes occurred, there was a fifty percent chance of individuals who lived alone permanently leaving the village and a fifty percent chance of households composed of two adults

[1] Excluding outstanding reconstruction loan liabilities.

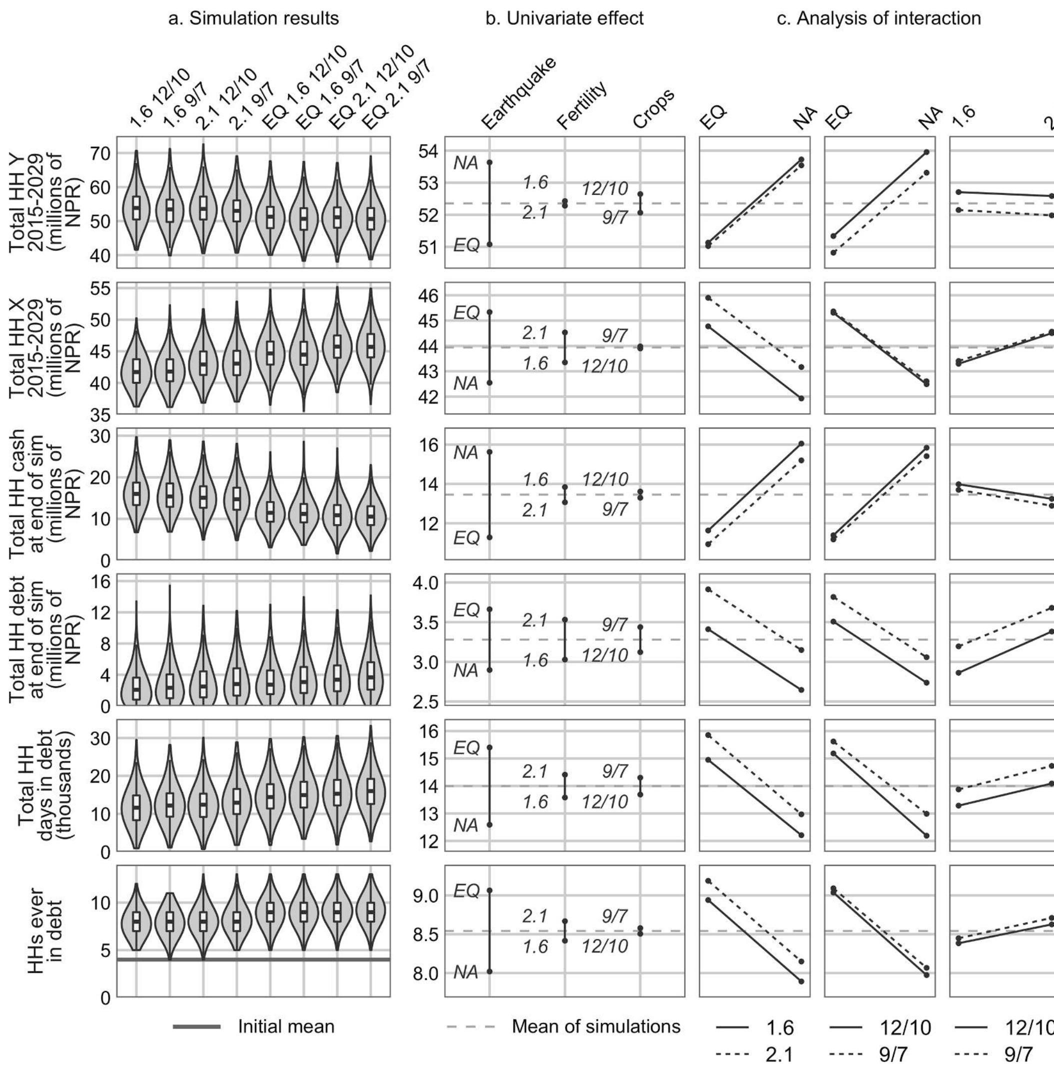

Fig. 3. Financial outcomes of the simulations. Explanation of codes: EQ and NA indicate whether the earthquakes are simulated or not; 1.6 and 2.1 indicate the average fertility rate; 12/10 and 9/7 indicate the half yield crop variability rate with the first number representing the rate for subsistence crops and the latter number representing the rate for cash crops.

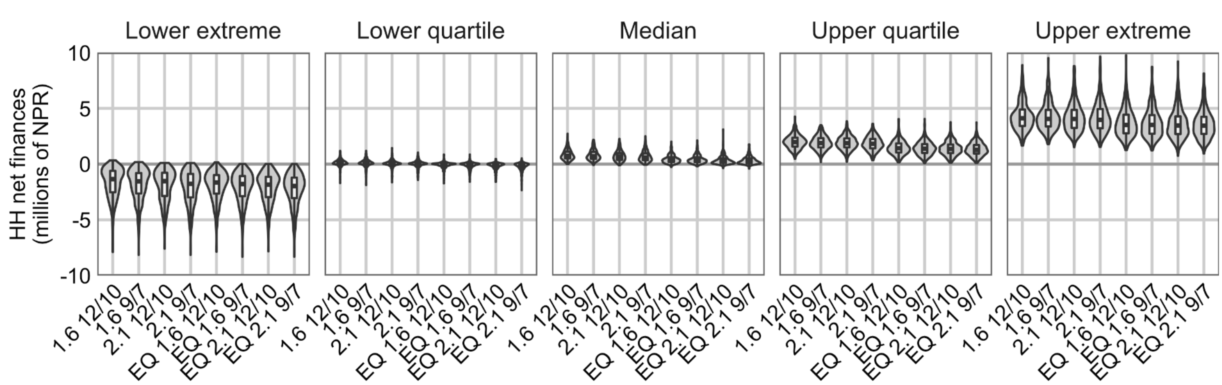

Fig. 4. Violin plots showing the minimum, first quartile, median, third quartile and maximum net finances of households at the end of the simulations for the eight scenarios combinations.

– at least one of whom has salaried employment – permanently leaving the village if one of those adults had a salaried job. It is therefore inevitable that the average number of households at the end of the runs is lower when the earthquakes are simulated compared to when they are not. However, the long-term impact on village demographics and economics of either household type migrating differs notably. Individuals in lone-member households are typically from older cohorts and their estates are already destined to be dissolved upon their deaths. Their migration merely hastens that dissolution. In contrast, the salaried two-adult households are typically in the early stages of establishing a family, so their loss has much longer lasting demographic consequences when looked at from a village level perspective. In the model, this has

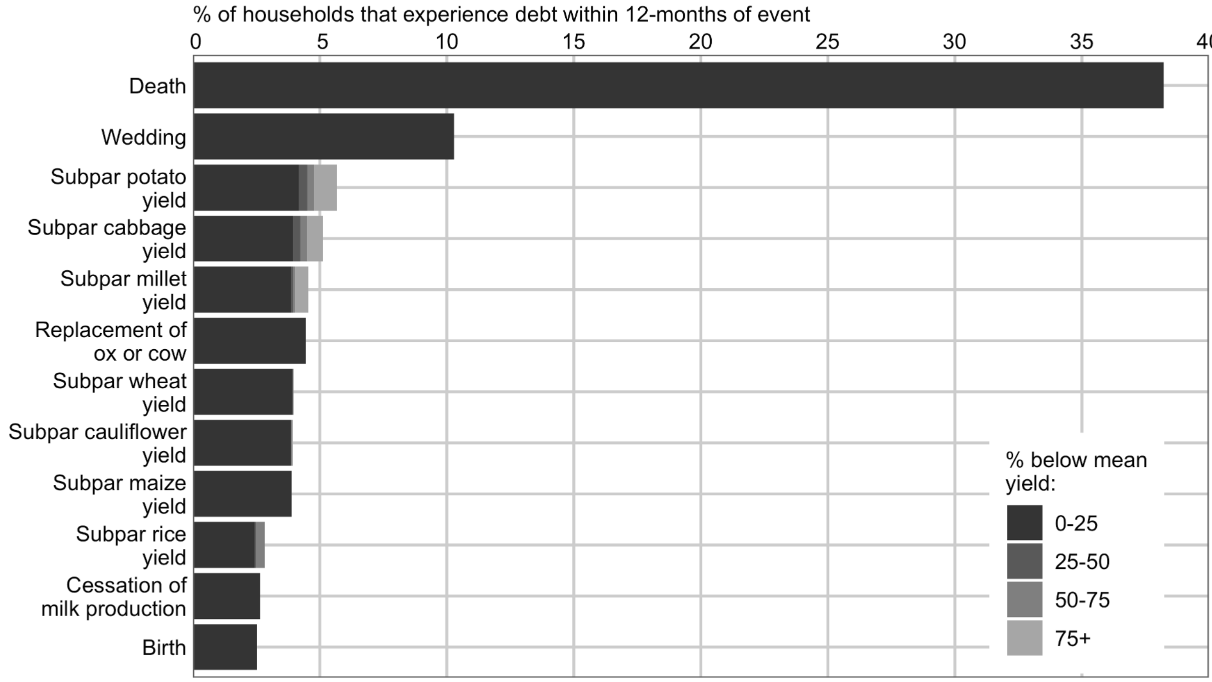

Fig. 5. The average percentage of households that had positive net finances that experienced debt within 12-months of given events occurring. The results are an average of all the scenario pathway combinations. Households are only registered as experiencing a subpar harvest if they grow the crop in question.

Table 1
Kendall's tau-b correlations showing the association between various household attributes and changes in household net finances over the course of three time periods.

	Change in household net finances correlation coefficient		
	2015–2019	2020–2024	2025–2029
Fields	0.022	−0.081	−0.045
Polytunnels	0.307	0.313	0.313
Members	0.023	−0.076	−0.152
Youth dependents	−0.001	−0.054	−0.149
Non-earning adults	−0.192	−0.289	−0.192
Waged members	0.238	0.113	0.14
Salaried members	0.269	0.327	0.392
Members abroad	0.238	0.113	0.14
Pensioned members	0.249	0.21	0.188
N	6527	4392	4378

little consequence for remaining households but, in reality, would reduce the local labour pool and could have a notable social impact on the community. A study in Italy which looked at the impact of the 2009 L'Aquila earthquake on quality of life and well-being found that many elderly residents in the mountainous areas affected struggled as their friendship and support networks fragmented due to households relocating (Giuliani et al., 2014). The possibility of this should be considered by those working in post-disaster contexts.

Economically, the earthquakes have a very profound impact. In the period immediately after the initial earthquake, households experienced both income and expenditure shocks, followed by an extended period of substantial reconstruction loan debt and repayment obligations. The implications of this varies between households. Higher income households were able to absorb the initial shocks and make loan repayments with relative ease, so their wealth accumulation slowed but was not halted. Many middle- and low-income households, by contrast, had to curtail spending on luxuries to meet repayment obligations and often found themselves flirting with debt. Because many household cash stocks were depressed over an extended period by reconstruction loan repayments, households often ended up financially vulnerable to the effects of other shocks and stressors. Consequently, earthquake affected simulations saw higher numbers of households getting into debt at some stage during the simulation and a greater total number of household days spent in debt across the village. Such long-term financial struggles have been documented following other disaster events: Dash et al. (2007) found the financial impact of Hurricane Andrew in 1992 was still felt by many households a decade later.

Also notable with many of the low- and medium-income households were longer reconstruction loan repayment periods than was the case for higher-income households due to the deferment of some (or sometimes many) repayments. Difficulty repaying reconstruction loans chimes with media reports suggesting many real-world earthquake hit households in Nepal are struggling with repayments (Starr, 2018). Arguably, the reconstruction loans had least impact on households already trapped in debt when the loans were issued and who remained in debt during the remainder of the simulation as they will not have made any repayments. However, these households were still exposed to the earlier economic consequences of the earthquakes.

The findings highlight the need for greater thought as to how post-disaster reconstruction is financed, with the impact that financing mechanisms can have on the future financial vulnerability of households requiring more detailed consideration. Potential alternatives to the approach used in Nepal are discussed by Freeman (2004) and by Linnerooth-Bayer, Hochreiner-Stigler and Mechler (2012). Our findings also underscore the importance of considering differences in household level impacts and recovery pathways so that support can be better targeted (Michaels et al., 2019).

4.1.2. Fertility rates

Fertility rate scenarios were only relevant to households in the model that contained couples of child-bearing ages. Even then, the impact of the scenarios was only stochastically felt. Nevertheless, when the simulations are considered collectively, the impact is clearly discernible. The average villager count under the higher fertility rate scenario is 3.5 persons more than that under the lower fertility rate scenario, while the average household size increases by 0.28 persons, with the main impact of this felt within the households to whom the children are born. Within the fifteen-year period of the simulation, this impact primarily takes the form of higher food, education, and festival expenditure for households with more children. Affected households are mostly able to absorb such costs relatively well as the fertility rate scenarios have little impact on the overall number of households who get into debt during the simulations. Nevertheless, households with more children find it slightly harder to get out of debt as their margins are more squeezed. Indeed, the total number of household days in debt tends to be slightly higher under the higher fertility scenario.

The main reason for fertility rates having little effect on debt entry rates is that parents of children born during the simulations tend to have relatively good income, often working abroad or in salaried jobs. They are members of a generation which by village standards, is doing relatively well, financially. Furthermore, the actual costs of supporting children are not all that high. The variable cost of additional members (e.g. food and education expenses) is often small relative to other costs (e.g. agricultural activities) (Libois and Somville, 2018).

Had the simulated period run beyond 2030, the impact of the fertility scenarios would have become more multidimensional and consequential. Children born in the period up to 2030 would impose greater costs as their food needs increased, as they undertook further education, and as they got married. As some began to work, they would then have transitioned from being net spenders to net earners, morphing from being burdens on their households to potential assets. Additionally, as they married, girls would have left the village, while the boys would have been joined by wives, further reshaping village demographics and bringing about additional household fission. Consequently, the effect of fertility rates on village demographics and economics needs to be recognised as ever evolving. This assertion is consistent with findings within the demography literature that suggest changing age structures are what matter most from an economics standpoint, rather than the population growth rate *per se* (Eastwood and Lipton, 2012; Kelley and Schmidt, 2007).

As the initial demographic conditions of the model play an important role in both enabling and constraining the subsequent evolutionary dynamics, changing those substantively would change the dynamics (Miller and Page, 2009). Consequently, the demographic findings are considered specific to the case study site.

4.1.3. Crop variability

All households in the model engage in agriculture and were affected by the crop variability scenarios. However, the nature and degree of their exposure varied due to differences in land holdings and crop strategies, and in their reliance on agriculture as an income source. The consequences of changing the degree of crop variability were therefore somewhat heterogenous across the simulated village, again demonstrating the importance of scale considerations when conducting vulnerability assessments. Households with large land holdings were most affected in absolute terms, especially in respect to changes in cash crop variability. These households tend to grow far more cash crops than households with smaller land holdings. Households with no off-farm income sources were usually the most financially vulnerable to the effect of higher crop variability because they were particularly reliant on agricultural income. These findings are consistent with those of Rurinda et al. (2014), Williams et al. (2016), and Lopez-Ridaura et al. (2018).

The higher rate of crop variability had a slight negative effect on household net earnings and a slight positive effect on the total number of days in debt. However, it had little impact on the total number of households to ever get into debt. This suggests most households are able to absorb the financial consequences of the modelled increase in crop variability reasonably well. As households base their spending on conservative forecasts of their future finances, those somewhat vulnerable to getting into debt will typically have given themselves some leeway. Also, poor harvests do not have an immediate negative impact on household finances unlike expenditure shocks – they constitute financial disappointments rather than losses *per se*. Consequently, households have time after the harvests to try to mitigate the impact (Hussain et al., 2016; Trærup and Mertz, 2011).

Differences in crop variability had no discernible impact on village demographics – there are no mechanisms in the model for this. However, as the impacts of climate change on agriculture in the Mid-Hills intensify, individuals and households may increasingly abandon agriculture and migrate to urban settlements (Bardsley and Hugo, 2010).

4.2. Interaction of stressors

Stressors can interact in nonlinear ways, fundamentally changing the nature of the stressors from what they would be when operating alone (Crain et al., 2008; O'Brien et al., 2009; O'Brien and Leichenko, 2000; Olsson et al., 2014). For example, McCubbin et al., 2015 argue that livelihood vulnerability in Funafuti, Tuvalu, is a synergistic product of climate and non-climate stressors (2015). However, in this study, no qualitatively meaningful interaction effects between the earthquake, fertility rate, and crop yield scenarios were observed in respect to any of the response variables. Instead, the stressors were found to simply compound the effect of one another in an additive fashion. While preferable to discovering synergistic effects, this does not mean that such effects do not come into play with other combinations of stressor experienced by Nepalese smallholder communities. Given the absence of qualitatively meaningful interaction effects in the simulations, we focus in the remainder of the discussion on the role that individual stressors play and on the additive impact of multiple stressors.

Despite the absence of synergistic effects, stressor co-occurrence clearly poses a challenge for many mountain households. Individual household experiences in the simulations show that concurrent and successive stressors often contribute to households getting into financial difficulties. The impact of one stressor reduces the capacity of households to cope with others. For example, the need to repay reconstruction loans in half of the simulations compromised abilities to build the kind of financial buffers that would enable them to cope with the impact of disappointing harvests. Households' capacities to cope with other shocks and stressors were also compromised, as illustrated by Fig. 6. Here, finances of both households had been on an upward trajectory prior to reconstruction loans being issued. Once repayments began, finances of Household A started to progressively erode, while those of Household B effectively plateaued. Significantly, Household A subsequently experienced the death of two members, while Household B lost an important source of income – milk sales. The former household fell into debt, while the latter narrowly avoided it by curtailing non-essential spending. Expenditure of limited resources to respond to a stressor or set of stressors, only to increase household vulnerability to future risks because they have eroded their asset base, is a key theme in the multiple stressors literature (McDowell and Hess, 2012). There is no magic bullet solution. However, chipping away at the threat posed by individual stressors should enhance the capacity of households to confront them as collectives (Antwi-Agyei et al., 2017), especially if impacts are essentially additive.

In addition to deaths and loss of milk production, the model also accounts for households being affected by weddings, the costs of replacing ox or cows, and births – events that can similarly have negative financial repercussions and which can be classed as shocks or stressors. As Fig. 5 showed, deaths are clearly the most significant event economically, being associated with substantial funeral expenses and, potentially, robbing households of earners, or affecting livestock and agricultural strategies. Studies in Vietnam (Wagstaff, 2007) and Kenya (Yamano and Jayne, 2004) concur, with households typically experiencing a decline in income in the region of 26–40%. Given this, development practitioners should consider prioritising support to bereaved families. Weddings have similar implications but are less costly and marrying individuals will have often already been financially independent from their parents' household, explaining why weddings appear less potent as precipitators of financial difficulty.

The percentage of households entering into debt following subpar

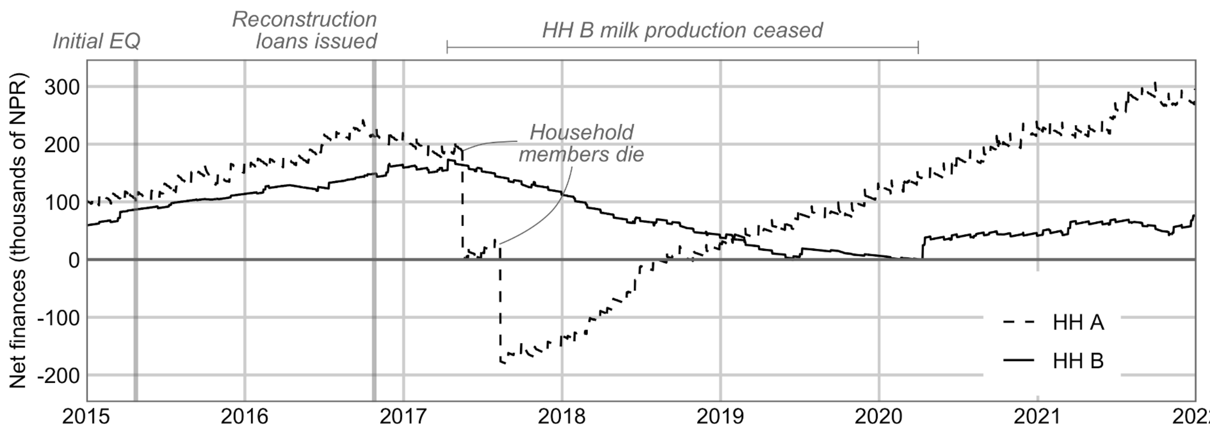

Fig. 6. Example of two households that experienced multiple stressors (taken from seed 3 of the EQ-16–9 scenario).

crop yields is only in the mid-single digits. This suggests that despite considerable literature focusing on vulnerability of mountain smallholders to climate change and other contemporary stressors (Gerlitz et al., 2017; Montaña et al., 2016; Panthi et al., 2016; Wang et al., 2019), regular happenstance can be just as important, if not more so. By narrowly focusing on topics that are in academic vogue like climate change, demographic change, and economic change, some of the biggest and more mundane reasons why households get into trouble are neglected. For example, Nielsen and Reenberg (2010) found that in Tuvalu non-climatic stressors were often considered more immediately pertinent to people's lives than climate change, even though much of the academic attention that Tuvalu commands is focused on the latter. Another important insight is that judgments on the significance of a stressor or shock can be strongly influenced by the scale at which such events are viewed. A poor potato harvest may have a larger overall impact on village finance statistics, but a single death or marriage in most cases will be more consequential at household scale. Titeux et al. (2016) raised a similar point in a study on the threats to biodiversity. Specifically, they considered the factors that are driving land-use change, noting that although large-scale forces linked to economic globalisation are the prime drivers internationally, actual changes in land-use are largely locally determined. Likewise, Antwi-Agyei et al. (2017) found that stakeholders in Ghana perceived stressors differently depending on whether they viewed them from a local level perspective or a district level perspective. For researchers and decision-makers to develop a truly rounded understanding of stressor contexts, they thus need to consider those contexts at a variety of different scales and remain open minded as to what may be significant.

While the scale of the costs involved in deaths and weddings are the main reason for their potency, additional factors may contribute to them being so financially harmful. An important distinction between deaths and weddings and the likes of subpar harvests and cessation of milk production is that, financially, the impact of the former is primarily felt in terms of expenditure, while the latter chiefly affects income. Expenditure shocks and stressors are generally more immediate, while income shocks and stressors are more gradually realised. The latter therefore allow households more time to react to their newly realised reality and to, ideally, avoid financial difficulties. These findings are in line with research by Cui and Huang (2017) in rural China which similarly found expenditure shocks to be more impactful than income shocks.

4.3. Attributes shaping households' capacities to cope with stressors

The correlation coefficients in Table 1 show that off-farm income sources and tomato cultivation are the attributes most strongly associated with households performing well economically and therefore reducing their underlying vulnerability to stressors. Salaries provide a substantial and regular income. As village education levels improve, salaries are likely to become increasingly central to many mountain households' income. The value of tomato cultivation is perhaps surprising here. It is a relatively new addition to the livelihood mix in Namsa having been brought to the village by an INGO initiative in 2012, but the relative importance of tomatoes as an income source was difficult to gauge as the crop tends to be sold *ad hoc* over a few months. For additional households to benefit from the opportunity such high-value crops offer, they will need initial financial or material support as there are relatively high start-up costs. Given the apparent effectiveness of tomatoes boosting household earnings, there is a strong case for such support being provided.

Land holdings have very little correlation with financial performance. Historically, land has been among the most important household assets (Crone, 2013), but the simulation results suggest agriculture is now substantially economically subordinate to off-farm livelihoods and high-value crop cultivation. For some households, agriculture and livestock are the only source of income so having sufficient land holdings will remain important, but it appears that scaling agriculture brings little additional return. This is likely due to the inherent difficulties mountain farmers face in competing with lowland agriculture – a result of the complex terrain, shallow soils, and poor connectivity (Gerrard, 1990; Körner et al., 2005).

Of the household types generated at initialisation, the lone individual and lone couple structures will typically be endowed with fewest attributes and assets associated with strong financial performance over time. These households tend to be composed solely of members who are either retired or engaged in short-term labouring and who are nearing retirement. Only occasionally will they have pensions or remittance income. Consequently, they will often be reliant on on-farm livelihood activities so their income will be relatively low, and they will be particularly vulnerable to crop yield and livestock shocks. Nevertheless, because of their demographic circumstances they will never face costs associated with weddings and supporting children, and one member households never deal with the financial aftermath of funerals. Other household types that do have to deal with such events typically have more working age adults, which increases the likelihood they will have off-farm income sources. However, sometimes households lose their off-farm income earners increasing their dependence on on-farm livelihoods, unless they are entitled to inherit a pension. Overall, older lone individual and lone couple households are more vulnerable to the impact of shocks and stressors, but the other household types face a greater diversity of potential financial shocks and stressors. These differences should be taken into account when interventions are planned – household needs differ, even within villages (Gautam and Andersen, 2016; Gentle et al., 2014).

Data in Table 1 indicate that the number of children a household has had little correlation with economic performance over the first ten years of the model. During the final five years, the correlation between youth dependents and change in household net finances turned more negative ($\tau b \geq -0.149$, $p < 0.01$). This is likely due to an increase in average age of youngsters over time (see population pyramids in SI *Appendix 6*). The older the children, the greater the costs associated with supporting them so the greater their financial consequence. Indeed, many aspects of household circumstances are dynamic. Consequently, household fortunes and their degree of vulnerability is liable to change over time. With this in mind, development practitioners should consider how circumstances might evolve before deciding who is most in need of support and how that support is best delivered, otherwise interventions may only be effective in the short-term.

5. Conclusion

We used an ABM approach to explore the impact of multiple stressors on mountain communities up to 2030. Notably, we found no evidence of meaningful interaction effects between the stressors that were considered, but the potential importance of individual, concurrent, and successive stressor experiences was evident. The simulations additionally provided important insights into the role of happenstance and history in determining outcomes and brought attention to factors and processes which had not previously been highlighted in the stressor literature – e.g. animal lactation cycles. The ABM approach excelled in allowing examination of "what if?" questions in a scientifically rigorous fashion, with the potential effect of different stressors bound to plausible ranges (Epstein, 2008). It also enabled investigation of the heterogeneous impacts of stressors on households and enabled a more holistic approach to study of multiple stressor experiences than is usually possible, considering the interplay of processes that operate over radically different temporal and spatial scales. Insights provided through this approach offer potential to improve both resilience planning for multiple stressors and targeting of support towards vulnerable groups.

Going forward, model realism could be improved by imbuing households with greater agency, particularly when it comes to managing their finances. Another valuable step would be to conduct a fresh validation exercise using contemporary field data so that the long-term performance of the model can be assessed.

CRediT authorship contribution statement

Nicholas Roxburgh: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Lindsay C. Stringer:** Conceptualization, Methodology, Writing - review & editing. **Andrew Evans:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Raj K. GC:** Conceptualization, Validation, Writing - review & editing. **Nick Malleson:** Methodology, Supervision, Writing - review & editing. **Alison J. Heppenstall:** Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2020.102203.

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